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Embodied Energy Optimization of Steel-Concrete Composite Beams using a Genetic Algorithm

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Abstract

The optimisation of structural performance is acknowledged as a means of obtaining sustainable structural designs. The minimisation of embodied energy of construction materials is a key component in the delivery of sustainable future designs. This study attempts to understand the relationship between embodied energy and structural forms of composite floor plates repetitively used in multi-storey buildings, and highly optimise the form to minimise embodied energy. As a search method based upon the principles of genetics and natural selection, Genetic Algorithms (GA) have previously been used to optimise composite beams and composite frames for cost and weight objective functions. Parametric design models have also been presented in the literature as an optimisation tool to optimise steel floor plates for both cost and embodied carbon. In this paper, a Matlab algorithm incorporating MathWorks global optimisation toolbox GA and in accordance with Eurocode 4 design processes is employed to optimise a composite beam for five separate objective functions: maximise span length, minimise beam cross section, minimise slab depth, minimise weight, and minimise deflected shape. For each of these objective functions, candidate designs are assessed for embodied energy to determine individual relationships. It is concluded that correlation can be derived, and collective relationships between design and state variables as well as embodied energy can be determined.

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1. Introduction

This paper is part of a multi-dimensional industry-funded research project that studies the utilisation of optimisation algorithms to optimise steel-concrete composite structures in terms of their embodied energy demand. As a search method based upon the principles of genetics and natural selection[1] Genetic Algorithms (GA) have previously been used to optimise composite beams[2,3,4] and composite frames[5] for cost and weight objective functions. Parametric design models[6,7] have also been presented as an optimisation tool to optimise steel floor plates for both cost and embodied carbon. In this study, a Matlab algorithm is presented incorporating MathWorks global optimisation toolbox GA[8] and utilising Eurocode 4[9] design processes to optimise a composite beam for five separate objective functions: maximise span length, minimise beam cross-section; minimise slab depth, minimise weight, and minimise deflected shape. For each of these objective functions, candidate designs are to be assessed for embodied energy[10] to determine individual relationships. Following, Section 2 describes current practice into the optimisation of steel-concrete composite beams; the genetic algorithm as a means of optimisation, and the importance of this work for the aims of the broader research area. Section 3 defines both the structural design as well as the life cycle energy analysis processes implemented in this work. Section 4 describes how the GA function of MATLAB Global optimisation toolbox is implemented. In section 5, the outcomes of this optimisation are reviewed and discussed, and the implications of this work and the next steps of this broader research area are summarised.

2. Optimising Steel-Concrete Composite Structures

2.1 The Genetic Algorithm

The GA method is a metaheuristic search method based upon the process of natural selection [1]. Instead of the evolution of an organic species in response to external conditions, GA is a method in which the fitness of candidate designs is assessed against user-defined conditions and developed to produce a design that fits these conditions best. In operation, the GA utilises the following five steps [18]:

1) From input parameters, populations of candidate solutions are randomly generated.
2) The performance of a candidate solution within the population is determined against defined fitness functions.
3) Repetition of: selection of pairs of parent solutions, random crossover to produce candidate solutions, and mutation of offspring solutions.
4) Form a new population with these offspring solutions.
5) Repeat this process until an optimal solution has been returned.

2.2 Optimisation of Steel-Concrete Composite Beams

Utilising GA as an optimiser for civil engineering structures has featured in recent previous studies. Particularly for steel-concrete composite structures, GA has been implemented previously for cost optimisation by Panchal[2], Alanka and Chaudhary[3], and Senouci and Ansari[4], and GA has also been implemented to optimise composite frames for weight by Artar and Daloglu[5]. Eleftheriadis et al.[6,7] have previously experimented with the use of parametric design models to optimise steel floorplates to minimise for cost and carbon footprint. However, the optimisation of steel-concrete composite beams for embodied energy content by the utilisation of GA is yet to be undertaken.

2.3 Aims of this Study and Implications for Future Work

The steel-concrete composite beam is a complex structural system and it is a common structural element for floorplates, thus, it is the main focus of this study. To determine how design and variations amongst the properties of the steel-concrete composite beam impact upon the embodied energy content of the structure, the following objective functions are determined: minimisation of the universal beam (UB) section – objective function 1; minimisation of depth of the concrete slab (d_{slab}) – objective function 2; minimisation of overall weight of the composite beam – objective function 3; maximisation of the span length of the composite beam – objective function

4; and minimisation of the deflection of the composite beam – objective function 5.

MATLAB was employed to assess the ultimate (ULS) and serviceability (SLS) limit states of the composite beam in accordance with the design codes. It is proposed to utilise the MATLAB app Global Optimisation Toolbox[8] GA optimiser to calculate these minimisations and maximisation. The learning outcomes of this study are to be used to further refine the optimisation process for composite beams embodied energy content, and to progress to the optimisation of more complicated composite grid and floorplate structures.

3. Methodology for Structural Design and Life Cycle Energy Assessment

3.1 Structural Form

The structure in question is a single steel-concrete composite beam, comprising a universal I beam section, profiled steel sheeting, shear connectors, and a concrete slab with steel mesh reinforcement. This form of construction is common for a variety of building types, including high rise buildings. The beam is assumed to be simply supported and can be considered as either a primary beam spanning between two columns, or a secondary beam spanning between other beams.

3.2 Actions upon the Structure

With the omission of columns and lateral stability systems, only load cases in a vertical direction are to be considered for this work. These are for actions on the structure both during the construction stage as well as during the composite stage after the curing of the concrete slab. Calculation of permanent and variable actions are in kN/m^2. For the construction stage, permanent action g_k is calculated as the sum of both the steel cross-section and the profiled steel decking. Variable action q_k is the sum of the construction loading and the wet self-weight of the concrete slab. For the composite stage, permanent action is calculated as the sum of the steel cross-section, profiled steel sheeting, dry self-weight of the concrete slab, and an assumed loading for finishes. Variable action is taken as $2.5kN/m^2$ for a general use office area above ground level[15]. The maximum values for both g_k and q_k are taken as governing and adopted to calculating a combination of actions (F_d) in accordance to Eq. 6.10 from Eurocode 0[14], Partial safety factor for the permanent action γ_g is taken as 1.35, and for variable action γ_q is taken as 1.5 from the UK National Annex to Eurocode – Basis of Structural Design BS EN 1990:2002+A1:2005[21].

3.3 Ultimate Limit State Verification

With the design combination of actions calculated, the design moment $M_{y,Ed}$ and shear force V_{Ed} acting upon the structure are determined. Next, design checks in accordance with the Eurocode 4: Design of Composite Steel and Concrete Structures BS EN 1994-1-1:2004[9] are undertaken. Bending checks are undertaken for the moment capacity with full shear connection ($M_{pl,Rd}$), degree of shear connection (R_q) and then the moment capacity for partial shear connection (M_{Rd}). Shear checks are undertaken in accordance with the Eurocode 3[17] and Eurocode 4[9]. Finally, the transverse reinforcement is designed[20], and the concrete strut for crushing is checked in accordance with Eurocode 2[16].

3.4 Serviceability Limit State Verification

For determining the deflected shape of the structure, the following assumptions are made first:

- At the construction stage, the beam alone is assumed to have insufficient resistance to lateral-torsional buckling and will be fully propped, thus for this scenario, there is no deflection of the beam.
- The beam is assumed to be an internal beam; therefore, relative humidity is assumed as 50%.
- It is assumed that the cement used for the slab is normal hardening, thus class = N.

At start, owing to the concrete component of the structure, the creep coefficients are determined from the input assumptions using Fig 3.1 of Eurocode 2[16] to determine the coefficients for concrete with 1day and 28day strengths. Total shrinkage strain is also calculated to Eurocode 2[16]. Effective flexural stiffness (EI_L) of the composite section is calculated for permanent, variable, creep and shrinkage conditions, and corresponding deflections (δ) calculated using general equation 1, and total deflections checked against limits in equations 2 and 3.

$$\delta = \frac{5}{384}\frac{e_d L^4}{EI_L} \tag{1}$$

$$\delta_{Total} \leq \frac{L}{250} \tag{2}$$

$$\delta_{Var} \leq \frac{L}{360} \tag{3}$$

3.5 Quantification of Embodied Energy

Candidate designs that meet the criterion for ULS and SLS verification will be subject to the Life Cycle Energy Assessment (LCEA) to quantify the embodied energy of the structure. Owing to the nature of the structure, operational energy is omitted from the whole life assessment, only the initial embodied energy EE_i of the structure will be quantified as per Eq. 4[10].

$$EE_i = \sum m_i M_i + E_c \tag{4}$$

Where m_i is the quantity of material (i), M_i is the cradle to gate energy content of the material (i) per unity quantity, and E_c is the energy used on-site for construction. As the form of the beam under assessment is not variable, i.e., a single simply supported composite beam, the energy consumption for construction is assumed to be constant, therefore is omitted from the assessment. Similarly, energy consumption for the transport of materials to the site is assumed to be constant, therefore is also omitted from assessment[10]. The Inventory of Carbon & Energy: ICE[19] is the most recognised database source of energy constants for materials. The boundary conditions for global values from ICE for the components of the structure consider energy embodied from cradle to gate, i.e., energy to extract raw material, and all processes to produce construction products up to, but not including transport to site. Material quantities m_i is to be calculated by the specific component geometries of the candidate designs. For simplification, quantified components are to be limited to, the steel universal beam, steel shear connectors, profiled steel sheeting, reinforcing steel, slab concrete. Supporting columns and connections are assumed to be constant for all candidate designs, therefore, can be omitted from the assessment. As a simple quantification of embodied energy in terms of total energy content in MJ of the structure, owing to the simplicity of the structure under analysis it was reasonable to adopt energy per weight as the unit of quantification. It is anticipated that as this work progresses to more complex floorplate structures, it may be more appropriate to utilise more functional units for quantification.

4. MATLAB Scripts for Optimisation

4.1 General MATLAB Script for Structural Design and Life Cycle Energy Assessment

To optimise the stated objective functions, a MATLAB script has been assembled to enable the processes denoted in Section 2 to be undertaken and incorporated with the GA optimiser within MATLAB Global Optimisation Toolbox. A script of this complete process is attached in Appendix A.

Part 1 – Actions upon the structure comprises lines 1-10 of the script, and determines the combined actions F_d in accordance to Eq. 6.10 of Eurocode 0. F_d is calculated applied to the overall floor area supported by the beam, as floor area is required as an input for later functions; a dedicated MATLAB function is utilised for this purpose. Design moment M_{Ed}, and design shear V_{Ed}, are also calculated in the part of the script.

Part 2 – Ultimate limit state verification comprises lines 11-145 of the script and determines the processes for verification of moment capacity, shear capacity, design of transverse reinforcement and crushing of the concrete strut stated within Section 3.3.

Part 3 – Serviceability limit state verification comprises 146-199 of the script and determines combined deflections due to; permanent actions, variable actions, creep effects and shrinkage stress in accordance with Section

3.4. Checks of allowable deflection areas also undertaken.

Part 4 – Life Cycle Energy Analysis comprises lines 200-232 of the script and determines the quantity of materials in terms of kg from calculated volumes or areas. These are multiplied by materials factors and the results totalled in accordance with the Section 3.5.

4.2 Implementing MATLAB Global Optimisation Toolbox GA

To implement the GA optimiser within MATLAB Global Optimisation Toolbox, initially the objective function needs to be presented as a MATLAB function. This requires establishing the respective general equation to determine the objective function, the corresponding parameters, and the corresponding variables. This function when saved is called upon as the fitness function or FitFcn within the GA script. Now the script for the GA can be constructed with MATLAB. To begin, the constants of the fitness function should be listed and assign values. Next, the remaining components for the GA should be defined. First, the fitness function should be called upon, and all variables (x_i) and parameters of this function should be included. Next, the GA number of variables (nvars) within the fitness function needs to be defined for the GA program. Next, the lower (lb) and upper (ub) bounds of the variables need to be included. These bounds apply a constraint upon the respective script by limiting the range of variables in line with the feasible variable limits. For multiple variables, these limits should have vectorised like so.

$[lb_1, lb_2, lb_i \dots]$

Then, the optimisation options (optimoptions) should be defined. This includes selecting the GA optimiser, establishing the number of generations, setting the stopping criteria of the program, and plotting of outputs. At last, these components are assembled in the following order:

```
[x,fval] = ga(FitFcn,nvars,[],[],[],[],lb,ub,[],options);
```

Where, x returns the variable values for the optimised objective function fval. Upon construction of this script, the process is ready to be initialised.

5. Optimisation of a Steel-Concrete Composite Beam

5.1 Minimisation of the Universal Beam Section – Objective Function 1

To begin, the structural design and LCEA script is given an initial candidate design to establish benchmarks for design moment $M_{Ed,}$ as well as an outputted, embodied energy content. This is done with the following components:

- A 305x102x25 universal beam with a span length of 6.0m, and bay spacing of 3.0m;
- A 130mm deep C25/30 concrete slab cast upon;
- COMFLOR® 60[11] profiled steel sheeting, with SMD19105 shear connectors[12].

The structure passes all ULS and SLS requirements and the energy output of this script is a total of 23493.6MJ for the entire structure. A breakdown of the material contributions to this LCEA can be seen in Table 1. With an M_{Ed} output of 119.4kNm, the moment capacity for full shear connection $M_{pl,RD}$ output is calculated as 257.8kNm. In accordance with the design code equation for moment resistance, the check value is 0.46, less than half the check value of 1.0, implying reduction of the UB is achievable. To minimise the UB section, the GA process is introduced to minimise the depth of the section (h_a) specifically. First, a fitness function ha_function is written in MATLAB, based upon the calculation for $M_{pl,Rd}$ rearranged to make h_a the subject. For the fitness function, $M_{pl,Rd}$ is set as the variable (x), where other parameters are retained as constants. The GA program calls upon ha_function as the required fitness function. The lower bound for $M_{pl,Rd}$ is set to M_{Ed} rounded to the nearest whole number; this is to constrain the GA to prevent determining a depth of beam that would fail ULS checks. The upper bound for $M_{pl,Rd}$ is set to the computed $M_{pl,Rd}$ of the initial candidate design. This is to provide a practical upper bound that would prevent a solution having a depth greater than the initial candidate design. With a single variable, nvars is set to 1. Finally, options are set to give a run of 50 generations with MATLAB default population sizes of 50. A stopping criterion of infinite generations (MaxStallGenerations) is also included to ensure convergence during test runs of the script. This option is included for completeness, however, is overridden by setting generations to 50. Finally, the best and mean outputs (fval) per generation are plotted against their respective generation (Fig. 1a.) to visualise the convergence of the GA to a solution.

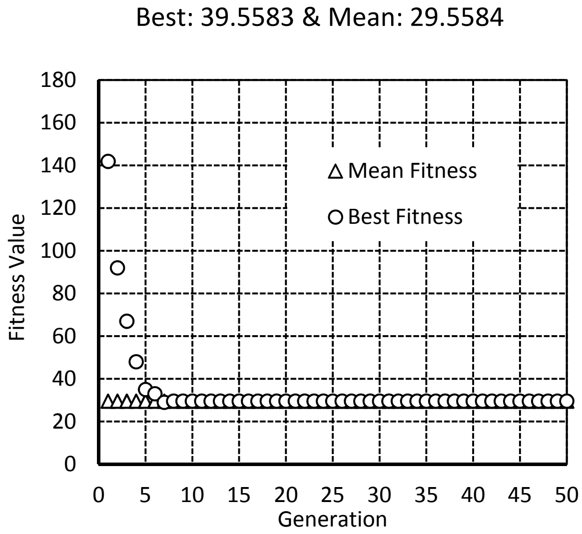

Fig. 1a. MATLAB plot of Objective function 1

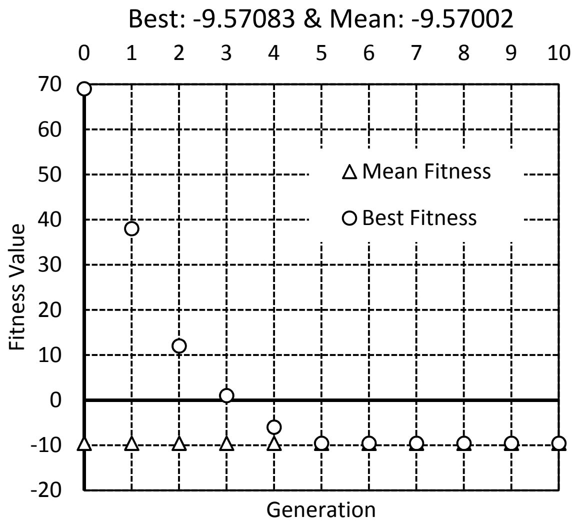

Fig. 1b. MATLAB plot of Objective function 2

For this objective function, convergence upon a solution occurs after 7 generations, giving a minimised h_a of 29.3mm. This depth is smaller than the stock blue book[13] sections and is unfeasible for the remaining design checks. To determine a solution that passes the ULS and SLS criteria, sections are manually cycled through until the minimum UB section of a 203x102x32 section is selected for assessment with the same span length and concrete slab depth as the initial candidate design. The total initial embodied energy of this revised design is 22367.5MJ, a 4.8% reduction compared to the initial candidate design. A breakdown of material contribution to this LCEA is included in Table 1.

5.2 Minimisation of Depth of the Concrete Slab – Objective Function 2

This optimisation utilises the same span length and UB section as the initial candidate design. To minimise the concrete slab depth, the GA process is introduced again, however, requiring a new fitness function to operate. The fitness function dslab_function is written in MATLAB, also based upon the design code. This time $M_{pl,Rd}$ is rearranged to make d_{slab} the subject. As with objective function 1, $M_{pl,Rd}$ is set as the variable (x), and the remaining parameters retained as constants. The GA program calls upon $d_{slab\_function}$ as the required fitness function. Lower and upper bounds for $M_{pl,Rd}$ are the same as for objective function 1 as the benchmark span and beam conditions from the initial candidate design are still valid. With a single variable, nvars is again set to 1. For this objective function, the MATLAB population size of 50 is retained. Initially the number of generations was kept at 50, however, as convergence occurs within 5 generations, this is reduced to 10 to enable the convergence to be better graphically visualised (Fig. 1b). Upon convergence, the GA gives a minimum d_{slab} of 9.57mm. Numerically this follows the design code accurately, however, reaping a negative value is essentially an unfeasible design. To determine a feasible solution, the shallowest slab depth in accordance with the manufacturer information[11] of 110mm is run along with the initial candidate design span length and UB section through the structural design and LCEA script. This structure passes both ULS and SLS criteria and returns a total initial embodied energy of 22534.6MJ; a 4.1% reduction of embodied energy compared to the initial candidate design. A breakdown of material contribution is included in Table 1.

5.3 Minimisation of Overall Weight of the Composite Beam – Objective Function 3

For this objective function, the span length and bay spacing are assumed the same as the initial candidate design. Consequently, as the floor area remains the same, the quantity of profiled decking and shear connectors remains the same. As the UB section has been minimised in objective function 1, and the concrete slab depth has been reduced in objective function 2, for this assessment a 203x102x23 UB with a 110mm slab is utilised. Running these respective inputs through the structural design and LCEA script, the structure passes ULS and SLS criteria and returns a total initial embodied energy of 21408.5MJ for the structure. A reduction of 8.9% compared to the initial candidate design. A breakdown of material contribution is included in Table 1.

5.4 Maximisation of the Span Length of the Composite Beam – Objective Function 4

Building on the reduction of total initial embodied energy from objective functions 1-3, this objective function seeks to maximise the span length for the reduced UB section and concrete slab depth. The output $M_{pl,Rd}$ of objective function 3 was calculated at 155.7kNm, with a F_d of 207,6kN imposed on the entire floor area. Substituting $M_{pl,Rd}$ for $M_{E,d}$ in the equation for design moment and rearranging, gives a theoretical span length of 7.832m for a 203x102x23 UB with a 110mm concrete slab over a bay spacing of 3.0m. However, running these inputs through the structural design and LCEA script, and the design fails both the ULS and the SLS criterias. Manually cycling through sections to ensure these criteria are met returns a design with a 254x102x28 UB. This returns a total initial embodied energy content of 29410.9MJ; a 25.2% increase for a 30.4% increase in span, and a proportionally 5.4% increase in total initial embodied energy, assuming a 30.4% increase of 21408.5MJ = 27916.1MJ.

5.5 Minimisation of the Deflection of the Composite Beam – Objective Function 5

Returning to a 6m span as per the initial candidate design, in accordance with the maximum deflection equation within the design code, the maximum deflection for SLS is limited to 24mm. As calculated by the structural design and LCEA script, objective function 3, with the lightest components, δ_{total}, is returned as 17.4mm. Running the structural design and LCEA script with the next largest UB section in the blue book[13] a 203x133x25, returns a deflection of 16.5mm, however, also returns a total initial embodied energy content of 21849.2MJ; a 2.1% increase when compared to objective function 3. A breakdown of material contribution is included in Table 1.

Table 1. LCEA Outputs for Objective Functions

Objective Function	UB Section	Slab Depth (mm)	Span (m)	EE_a (MJ)	EE_{sc} (MJ)	EE_{ps} (MJ)	EE_c (MJ)	EE_r (MJ)	EE_{total} (MJ)
Initial Candidate Design	305x102x28	130	6.0	6226.6	293.0	8143.0	4795.2	4035.8	23493.6
Minimised Universal Beam Section	203x102x23	130	6.0	5100.5	293.0	8143.0	4795.2	4035.8	22367.5
Minimised Depth of Concrete Slab	305x102x28	110	6.0	6226.6	293.0	8143.0	3836.2	4035.8	22534.6
Minimised Weight	203x102x23	110	6.0	5100.5	293.0	8143.0	3836.2	4035.8	21408.5
Maximised Span Length	254x102x28	110	7.823	8147.2	383.9	10617.0	5001.7	5262.1	29410.9
Minimised Deflection	203x133x25	110	6.0	5542.1	293.0	8143.0	3836.2	4035.8	21849.2

6. Conclusions

6.1 Summary of Results and Discussion

In this study, a MATLAB script has been produced to enable the verification of the ULS and SLS of a steel-concrete composite beam in accordance with the Eurocode 4 (parts 1-3). Additionally, LCEA is included to determine the total initial embodied energy content of the beams verified by parts 1-3 of the script. This enabled the GA optimiser from the MATLAB Global Optimisation Toolbox to be implemented for optimising five objective functions. Initially, this MATLAB script was used to run an analysis on a typical steel-concrete composite beam. The purpose of this initial candidate design was to establish benchmark conditions for structural performance in terms of ULS, SLS, and embodied energy quantification. These benchmark values served as parameters to begin the optimisation process, and also outputs for the optimised objective functions to be compared against. For objective function 1, by implementing the MATLAB script in conjunction with the GA optimiser, it was possible to reduce the UB section, by reducing the depth of the section h_a. Numerically, the output returned is accurate to the design process, but as minimum value signification smaller than the shallowest UB section readily available. This required manual intervention to determine the smallest UB section that satisfied all ULS and SLS criteria. Regardless, an overall reduction of an initial embodied energy of 4.8% was achieved. Moving forward, further refinement of the scripting is required to automate the selection of suitable UB sections. Objective function 2, aimed to reduce the depth of the concrete slab. Like objective function 1, it was possible to use the MATLAB script and GA optimiser to reduce the depth of the slab while numerically staying true to the structural design process. However, as the output returned effectively, eliminated any depth of the slab, further refinement to the scripting is required to ensure a minimum depth is achieved within practical limits. Assuming the shallowest practical depth of the slab, the total initial embodied energy can be reduced by 4.1%. Objective function e, aimed to reduce overall weight. A combination of the results of objective functions 1 and 2 and with consistent beam span/spacing as the initial candidate design, it was possible to determine a design that achieved a reduction of 8.9% of total initial embodied energy whilst satisfying all ULS and SLS criteria. Building upon the outputs of objective functions 1-3, objective function 4 aimed to maximise the span length of the composite beam. However, by manipulating the equation for design moment, by substituting a calculated capacity to give a theoretical maximum length. When proportionally comparing the energy content of the objective function 3 design, and design for objective function 4, a 5.4% increase in total initial embodied energy is returned. This is a result of the overall increase in material quantity. For objective function 5 aimed the combination of the reduced UB section and the slab depth resulted in the best performer for satisfying ULS and SLS criteria as well as minimised energy content. However, it was shown that increasing the UB section in an attempt to reduce the overall deflection returned a predictable increase in energy content, returned in this instance as a 2.1% increase against the initial candidate design.

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